should prepare his students for the diversity of legitimate points or view.

There is one other role a theoretician may take with respect to process control. He can believe in the effectiveness of working designs and take them as a challenge. Real designs and design efforts overcome the problems of high order nonlinear identification and complex design. Why can't theory reach some of these levels of combined simplicity and complexity? The theoretician should expect the challenge to effectively explain or extend practice to survive indefinitely.

Concluding Comments

There is a theory-application gap and we are all responsible. Because theoreticians normally lack practical associations to recognize the real theory needs or define where their theories could be applied, and practical people normally lack the insight to explain why theory fails and how applications can affect theory.

As electrical engineers, we are biased to a uniform treatment of control because our discipline lacks its associated application problems. But, historically, we have provided the theoretical underpinnings of all control teaching. On the positive side, this has forced us to generalize. On the negative side, it has caused us to fail to recognize potential application dependencies in the theory and philosophy of control.

This paper discusses process control in terms of its physical process, its system design human and business environment, and its relationship to the design and operation of large systems. Part of the difficulty of the theory-applications gap is that the technical nature of the processes to be controlled is only one of many factors to be taken into account in determining the "right" approach to control design and theory. This is as true of any other practical engineering activity as of process control. Every application area supports many points of view. Nevertheless these points of view can be recognized and catalogued. They should give rise to a more varied and useful body of theory and teaching practice than now exists.

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Distributed Computer Control for Industrial Process Systems: Characteristics, Attributes, and an Experimental Facility

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Abstract

The very rapid advances in digital hardware and the less rapid, but still significant, advances in computer software have led to the development of microprocessor-based distributed control systems by all of the major vendors of process control equipment. These systems have attracted very considerable interest on the part of the process industries.

This paper describes a laboratory facility, centered around a Foxboro SPECTRUM distributed control system, which will provide an experimental base for the motivation, development, and testing of analytical theory, methodologies, and engineering tools for the design and analysis of these complex control systems.

A discussion of the characteristics and attributes of distributed computer control is followed by an overall description of the laboratory facility. This includes a description of the control, communication, and computer components as well as the instrumented test-bed processes. Finally, an overview of several current and proposed research studies using this facility is presented.

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I. Introduction

With the continual improvement in computer hardware from microprocessors and digital signal transducers to mainframe computers and sophisticated data transmission techniques, there has been an increased use of computers for the control of industrial process systems. This has led to the design and implementation of distributed computer control systems, or the realization of control tasks on a multiple computer system. These complex systems have four general characteristics which serve to represent a large class of systems important in engineering application:

(i) Microprocessor and analog based controllers for first level control functions.
(ii) Minicomputers and large mainframes for higher level control functions.
(iii) Physically dispersed structure implying the need for a computer-to-computer communication system.
(iv) Centralized operator interfaces having access to all process variables, control variables, and system status indicators.

Primarily as a result of the low cost of microprocessors, memory, and peripheral interface chips, there has been a large increase in the use of these devices in industrial control systems. Not only has there been a development of microprocessor-based controllers to mimic the functions of analog controllers, but these new controllers have significant advantages over conventional ones, e.g., the range of functions which are available, the ease of altering the control algorithm, and the compatibility with other computer-based industrial control devices. However, if there is a need for very short response times, then either a dedicated microprocessor based controller having responsibility for only one or two loops, or an analog based controller is indicated.

While there are a large number of relatively simple control and signal processing functions appropriate for microprocessor or analog based devices in an industrial process environment, there remain many complex control tasks which are appropriate for execution on a minicomputer or large mainframe system. Note that by "control," the intention is to include the entire set of decision-making functions in an industrial process system. Thus, control tasks such as optimization, adaptation, scheduling, data base management, event logging, and management reporting are all more suitable for execution on a higher level computer system. A determining characteristic of these higher level control functions is that they do not have the stringent response time requirements of the direct control functions. Therefore, a large degree of operating system overhead costs may be tolerated at this level in order to have efficient allocation of computer system resources among the competing tasks.

The addition of a high speed computer-to-computer communication network to a collection of autonomous control computers allows the realization of true concurrency and resource sharing in a control system. The communication system is responsible for process data, program, command, and status information transfer among the control computers and devices.

The management, parameters, and the structure of the communication system play a critical role in the overall performance of the distributed system [1]. Consequently, the design of a distributed system must carefully translate the needs of the specific application into a communication topology, level and location of redundancy, set of operating rules, i.e., protocol, for the communication system. Commonly used structures include the loop, star, global bus, or hierarchical topology. Two recent texts [12, 13] and the articles [1–3] are excellent references to the concepts, methodologies, software, hardware and structure of distributed computer systems. Each structure can be accessed in a number of ways with each structure/access mode yielding different performance characteristics [2]. As a simple example, a star system has a reliability measure that depends critically on the reliability of the central switching unit. On the other hand, a bidirectional loop need not necessarily fail upon the failure of a single interface. Similarly, the communication delay of a loop structure can be expected to be higher than the delay of a shared global bus because of the additional delay imposed by information being routed through device interfaces along the loop. Even though there are significant problems and questions to be addressed in the design of a communication system for a distributed control application, the potential benefits are quite appealing from the viewpoints of modularity, ease of expansion, reliability, performance, and cost [3].

The operator interface is an essential component of a control system for a large industrial process plant. The need for displaying process information in a timely and appropriate manner is critical to achieving plant efficiency, safety, security, and integrated control. A computer control system having distributed intelligence and an associated computer-to-computer communication system can provide for an economically attractive solution for an operator interface system. In particular, the distributed system allows for a centralized display and command capability having access to all process variables, controller inputs and outputs, as well as system status indicators. Not only can a single unit of this type be incorporated in a distributed system, but additional operator interfaces of varying complexity can be conveniently located with only minimal modification or extension of the original system. In this context, the management reporting function can be approached in the same manner and with the same hardware as the primary operator interface. One need only provide the appropriate software for the computation and display functions required of the management/supervisory system. Of course, consideration of multiple access points to either a centralized or distributed data base describing the state of the control/process system presents considerable data base management problems. This is particularly true when error recovery and consistent state recovery are required in a real time environment [4].

The characteristics which have been attributed here to distributed computer control systems are general in nature and are possessed by most commercial general purpose process control systems. However, many distributed control systems exhibit only a subset of these characteristics because of their highly application-oriented design.

As a result of these characteristics, there are many potential benefits of *well-designed* distributed computer control systems. In particular, one can cite [5] advantages such as increased fault tolerance, reliability, and availability; natural implementation of hierarchical control algorithms, modularity, and flexibility; ease of design, realization and maintenance; evolutionary construction, and reduced wiring costs. It is important to realize that the specific set of characteristics, attributes, and *detailed* realization aspects of a distributed control system can very significantly affect

overall performance to the extent that potential advantages turn into significant disadvantages. Current research effort is being directed at some of these complex large scale discrete event design problems at Case Institute and elsewhere.

As noted, one of the significant advantages of a distributed system is the potential for increased "survivability." By this is meant the ability of the system to perform satisfactorily a given set of functions over a particular time horizon. This property is manifest in two distinct ways: fault avoidance and fault tolerance. In the context of fault avoidance, a distributed system allows the designer the flexibility of allocating redundancy, pretesting, and quality control to the extent that is required for a given component of the overall system. Therefore, if a given regulatory control function requires rapid response and tight control, then it may be appropriate to provide redundancy, at the *loop* level, for this function. On the other hand, if a loop is not critical or can tolerate a moderate response time, then it may be appropriate to allow for backup in a higher level processor and accepting some degradation of performance. By appropriately using fault avoidance techniques, the designer can achieve an economic solution to the problem of achieving a sufficiently high availability. On the other hand, the dynamic reconfiguration of one component to perform the functions or tasks of a failed component can also yield increased survivability. Of course, reconfiguration must be accomplished so as to assure adequate performance of basic functions. Clearly, this dynamic aspect of survivability also affects the economics of the problem solution by providing a complementary alternative to fault avoidance. Although commercially available systems exploit some aspects of fault avoidance, fault tolerance and fault containment techniques (i.e., the isolation of the effects of a particular fault or failure), they have generally limited reconfiguration capabilites. It is expected that the next generation systems will exhibit much more sophisticated dynamic reconfiguration features.

In many cases, the structure of a well designed distributed system reflects the control philosophy of the plant. In other words, there is a partitioning of computer responsibility, under normal operation, into various functions such as direct control, supervisory control, scheduling operations, management reporting and analysis. This results from a natural association of control tasks with computer attributes. For example, a microprocessor having limited arithmetic capability, rapid response time, and limited memory is well suited for performing a PID control calculation for several loops but not well suited for an identification algorithm computation. On the other hand, a minicomputer having considerable floating point capability, a relatively long response time, and considerable main and secondary memory might be well suited for a scheduling task execution but not for responding to an interrupt indicating a dangerous condition. Thus the distributed system lends itself to hierarchical control strategies in a natural way.

For industrial control applications, the cost of cabling is a significant cost of the overall project [6]. The use of a distributed system incorporating a digital data communication network allows for considerable cabling cost savings, increased security of data, and ease of process expansion in industrial process systems. Associated with this property is the capability to construct a system which evolves in time to meet the applications demands. In other words, the distributed system allows, to an extent depending on the overall system structure and communication system characteristics, an economic solution to changes made to an installed and operating system.

In summary, the proper design of a distributed system for a process/plant control application permits the realization of a wide variety of advantages which directly impact on plant performance, cost, and safety.

II. Description of the Distributed Control Facility

In order to investigate the problems outlined earlier and to provide an experimental test bed for the application of new methodologies and theory, a distributed computer control laboratory facility was developed as a joint effort of the Systems Engineering and Chemical Engineering Departments at Case Institute of Technology. The facility, being used for studies of distributed and hierarchical control, comprises a commercially available state-of-the-art Foxboro SPECTRUM distributed computer control system and several experimental and simulated process units. The Foxboro system is currently in place and fully operational. It consists of a sophisticated color graphics operator interface (VIDEOSPEC), a microcomputer based controller (MICROSPEC), two analog based controller units (SPEC 200), two host minicomputers (FOX 3 and PDP 11/34), and a high speed data communications system linking *all* the control system components.

The Case/Foxboro distributed control system is structured as a hybrid star/global highway topology shown in Fig. 1. There are several components interconnected in a star configuration at the Systems Engineering Laboratory and several components interconnected in a like manner at the Chemical Engineering Laboratory, with a coaxial cable (data highway) run of approximately 1,000 ft. between the sites. In general, characteristics of the FOXNET communication system provide for local or extended network communications, coaxial cable (with redundancy) runs up to 4.5 km, 1 megabit/second communication rate, and can handle up to 100 diverse stations. The communication protocol, similar to SDLC (Synchronous Data Link Control), uses several control fields, a variable length information field, header parity, longitudinal parity, and CRC (Cyclic Redundancy Check) computation and checking, automatic line break detection and redundant line switching, fallback to local network operation on loss of long distance communication, and a network structure which can easily be expanded or modified.

The microprocessor-based controller incorporates numerous control security features such as a secondary ac power source, a redundant controller with automatic switching, power supply (dc and ac) monitoring, basic controller functions in ROM, testing of control computations, watchdog timer and process input/output checking. In addition, the controller provides for implementing 60 control blocks which are realized in software and dynamically reconfigurable from the VIDEOSPEC or host computer. Some of the functions realized by the blocks include: a large variety of control algorithms, remote/local set points, logic functions, digital pattern recognition, adjustment of tuning parameters, alarm calculations, and calculator type arithmetic operations. These blocks may be independent of one another or interconnected to realize sophisticated control algorithms. Finally, the MICROSPEC accepts up to 30 components for digital and/or analog process inputs and outputs.

The FOX 3 and PDP 11/34 mini-

computers provide for higher level control functions in the system. Also sophisticated color graphics display capability of the FOX 3 can be exploited by configuring displays to meet the needs of an individual application. The FOX 3 permits programming in either a block structured higher level language (with functions similar to the MICROSPEC) or in a general purpose real time extended BASIC language. The PDP 11/34 contains a floating point processor, a floppy disk drive, 64K words of RAM, a fixed removable disk storage capacity of 7.5 M bytes, an AR11 laboratory analog data acquisition and control subsystem, and several input/output peripherals. While the FOX 3 connects directly to the FOXNET data communication system, the PDP 11/34 will be interfaced to the system through a general purpose protocol translator developed at Case.

III. Laboratory Process Units

A number of laboratory process units are available in the Chemical Engineering and Systems Engineering Laboratories to serve as experimental vehicles for a variety of research studies based on the Foxboro distributed control facility. These are equipped with sensors for the key temperatures, pressures, and flowrates; measurements are transmitted to the control system via standard electrical (analog) signals. The process units are also provided with diaphragm operated control valves and other actuating devices for implementing automatic control. As noted earlier, the two laboratories are linked via coaxial cable with various components of the Foxboro system resident in each laboratory. This provides flexibility in setting up different configurations of the distributed system.

The Chemical Engineering Laboratory includes, at present, the following experimental units:

(a) *Distillation column.* This is a 6-in. diameter, 15-tray column with reboiler and condenser. Instrumentation includes temperature measurements on each tray and various flow streams, flow measurement of feed and reflux streams, and flow control of heat input rate and reflux rate.

(b) *Tubular reactor.* This is a fixed-bed catalytic reactor set up for the styrene reaction. It is instrumented for measurement of feed flowrates and temperature distribution along the reactor. Control capabilities include the adjustment of the temperature profile.

(c) *Heat exchanger system.* This consists of three heat exchangers arranged in the series-parallel configuration shown in Fig. 2. Thermocouples provide temperature measurements for all input and output flow streams as well as at various points within the exchangers. In addition, electronic differential pressure (D/P) cells provide signals measuring the steam pressure and the flowrates of the liquid streams.

Experimental vehicles for control studies located in the Systems Engineering Laboratory include the following:

(a) *Liquid level control system.* This is a relatively simple single loop control system at present. A temperature control loop may be added later to provide interacting control loops and nonlinear behavior for studies of multivariable and adaptive control.

(b) *Air pressure control system.* This consists of several pressure tanks in series with flow restrictions in the connecting lines. A flow control valve regulates the flow into the first tank; a D/P cell measures the pressure in the last tank. Motivation for this setup is the inherent nonlinearity of the system dynamics.

(c) *Analog computer.* An EAI 580 analog computer provides the means for simulating a variety of dynamic processes for added flexibility in configuring distributed control problems. Input and output variables are represented directly as voltage signals compatible with the Foxboro system.

IV Research Studies

A wide range of studies are contemplated in the areas of distributed and hierarchical control as part of an ongoing research program in the "Control of Industrial Systems." This program is funded by a diverse group of companies

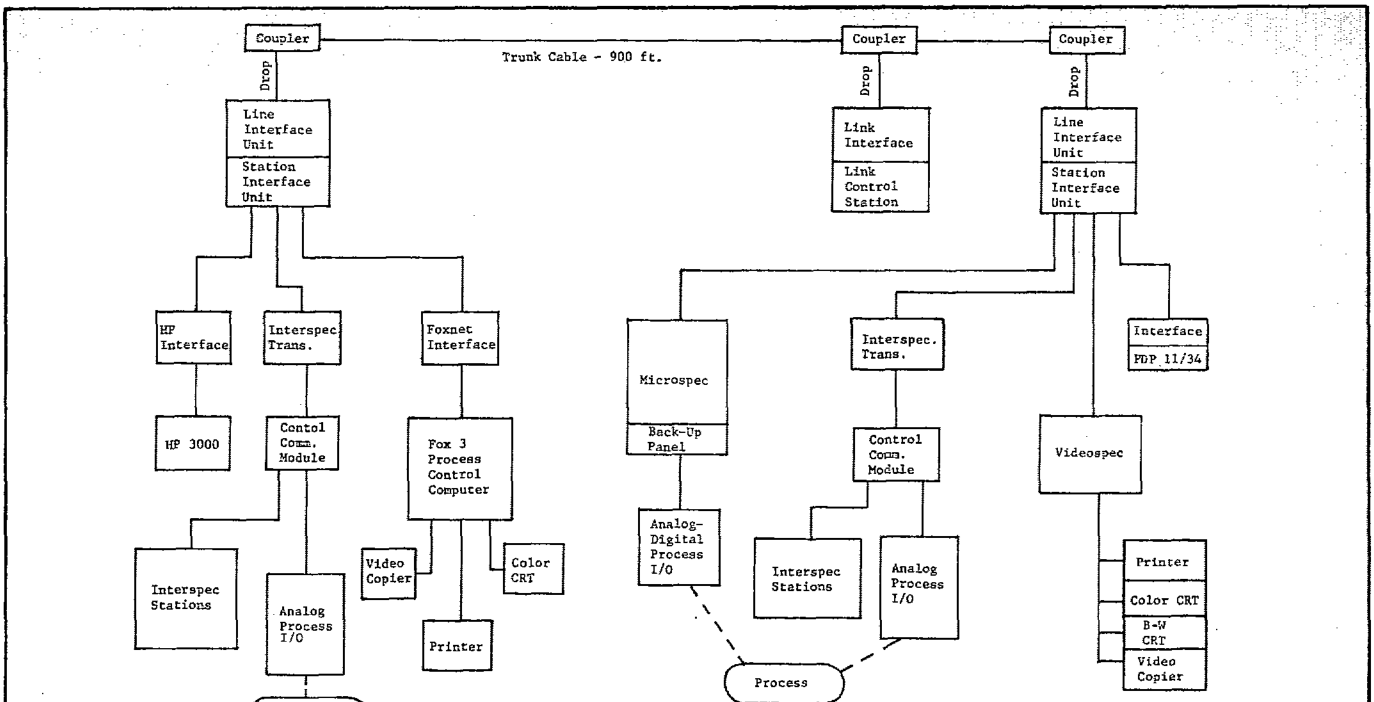

Fig. 1.

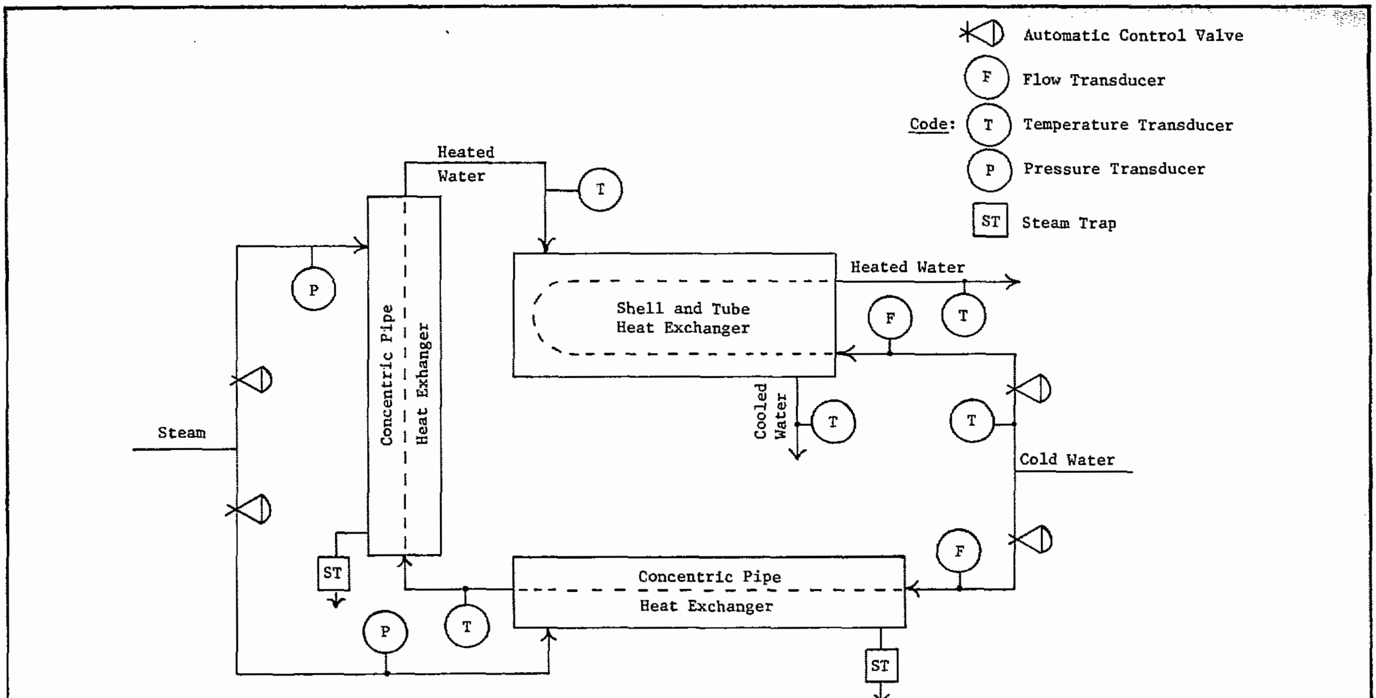

Fig. 2.

representing oil, chemical, steel, process control and other industries. The research is interdisciplinary with participation by students and faculty from chemical engineering, computer engineering, systems enginering and other disciplines.

Projects fall into two broad categories: (a) developing new control algorithms and techniques which take advantage of the features and capabilities of the new microprocessor-based hardware and distributed architectures, and (b) determining the limitations and constraints of current distributed systems and thereby formulating new approaches, techniques and methodologies for improving system performance. Research to apply self-tuning to the direct control functions in a distributed control environment is an example of the first category; studies of communications protocols and the efficacy of various architectures represent the second category. A sampling of projects currently active or under consideration is presented below:

1. *Measurement of performance of line-sharing systems.*

A systematic framework does not exist for evaluating the efficacy of various architectures for microprocessor-based distributed process control systems. In particular, questions of fault tolerance, software complexity induced by protocols, performance (bottlenecks, message delay, throughput, etc.) and modularity have not been addressed quantitatively in the literature.

The objective of a proposed study is to determine the effects of protocols, access arbitration, message insertion methods, and the location of distributed intelligence and control components on various performance parameters, including line utilization, message delay, throughput, message wait time, and response time. Experimental data will be drawn from the Foxboro distributed system.

2. *Hierarchical computer control structures for integrated control of process systems.*

In recent years, there have been increasing applications of computer hierarchies for the operation and control of industrial plants, e.g., steel, petrochemical, electric power distribution [9, 10]. However, there is a lack of an effective systems design methodology and, consequently, such hierarchies have been generally designed in an ad hoc manner, based on heuristic and subjective approaches to the problem.

We propose the construction of a system data management model in terms of an overall hierarchical-multiobjective structure [14]. This structure would clarify the relationships between the objectives of system operation and the corresponding data managment structures. It would also clarify both the justification for various control and analysis functions and their data management requirements. Structure dictates data and computational requirements but the hardware and software capabilities of the information system, in turn, influence the design of the hierarchical structure.

Major features of the hierarchical control approach [10, 15, 16] include:

(a) *Reduction of system complexity.* The hierarchical structure provides the basis for simplifying the system by: (i) decomposing it into weakly interacting subsystems, (ii) using approximate models of reduced dimensions and complexity, and (iii) aggregation of models and data.

(b) *System integration.* Since the subsystems in the multilevel-multiobjective decomposition are interacting, it is necessary to apply coordination at the higher levels of control in order that overall objectives and constraints are satisfied. The use of approximate and aggregated models are predicated on information feedbacks that relate the model to recent operating experiences with the subsystem described by the model. Anticipated results include design methodology with respect to (i) data base and data flow requirements for updating control models at each level, and (ii) the degree of aggregation associated with each level.

(c) *Decentralization.* A consequence of system decomposition is the opportunity to decentralize the control and data management tasks. This leads to a number of expected benefits:

(i) Reduction in data flow and data storage requirements because the

tasks are carried out locally, based on local data bases. Thus, the details are handled at the lower level and only the results (averaged or aggregated) need to be transmitted to other points in the system.

(ii) Design flexibility in the choice of hardware and software components to carry out the various tasks.

(iii) Better allocation of tasks between the human operators and the computer systems.

(iv) Improvement in system reliability because the control responsibilities are distributed, i.e., the effects of failures may be localized.

(d) *Temporal multilayer hierarchy.* A major factor influencing the choice of time scales in the temporal hierarchy [10] is the trade-off consideration relating the cost of exercising a control or decision-making action versus the benefits derived through improved performance as a result of the action. Costs include making the basic measurements, transmitting, processing and storing the relevant data, carrying out the computations, and implementing the final results. The trade-off leads to a partitioning of the control/decision variables into subsets based on relative time scales (or control periods) associated with each subset. This partitioning has an important impact on the design and performance of the distributed system with respect to such factors as data rates, storage requirements, and task priorities.

We propose to apply the Foxboro distributed control system to a set of process units which comprise a meaningful process system for the purpose of motivating realistic considerations of design methodologies, trade-offs and hierarchical structures.

3. *Integrated control of heat interchange in a process system.*

Heat exchangers are common components of industrial process systems for transferring heat from one process stream to another. This induces a coupling between the two streams with respect to both energy balance relationships and also dynamic interactions. The interactions greatly increase the problems of control because of multiple feedbacks, large time lags, etc.

The laboratory heat exchanger system provides a vehicle for studies of various advanced control approaches implemented in a distributed and hierarchical control environment. Studies may include considerations of the trade-offs involved with respect to the distribution of control and data processing tasks, requirements with respect to local and central data bases, and information flow requirements associated with the various control tasks.

Another class of studies contemplated for the heat exchanger system relate to the operational control problem, i.e., how to vary operating conditions and flow distributions in the network so as to achieve maximum thermal efficiency consistent with various constraints on temperatures, pressures, flowrates, etc., imposed by technological considerations. The related higher level control problem includes such tasks as the scheduling of shut-downs of heat exchangers for cleaning, diagnostics for on-line assessment of the performance of the various process units, diagnostics for contingency occurrences, etc. Included in the study are considerations of the trade-offs involved with respect to the distribution of control and data processing tasks, requirements with respect to local and central data bases, information flow requirements associated with the various control tasks, etc.

4. *Inferential Control*

Many industrial processes are inadequately controlled because on-line measurements of product quality are not feasible. An attractive solution to this problem is to use measurements of secondary process outputs, such as temperatures, to infer the effect of unmeasurable disturbances on the product quality. A control action can then be taken to maintain the product quality at a desired level. To be useful in an industrial environment, the control system must be relatively insenstive to modeling errors and measurement noise and must be economical to design and implement.

Research over the past several years has resulted in a design methodology for inferential control systems which appear to meet the above criteria [11]. It remains to show that the proposed inferential control can indeed be economically implemented. The microprocessor-based distributed control system offers considerable promise toward this goal and we propose to use the laboratory distillation column or the styrene reactor as the basis for initial investigations. A question of interest is the appropriate level at which to interface the inferential controller with the process. Current thinking is that the inferential system should directly manipulate the set points of first level controllers. This means that the supervisory controller would influence the process through the inferential control system. The defects, if any, in such an arrangment can be determined by applying the entire hierarchy in a simulated industrial environment such as that provided by the experimental facility described above.

5. *Self-tuning regulators*

In typical process control applications, the controller implements a standardized linear algorithm (e.g., proportional plus integral control) on a plant that is nonlinear and perhaps time-varying. Since the system can operate over a wide range of inputs, the dynamic behavior of the closed-loop system may change significantly over time. There is considerable interest, therefore, in algorithms to update the controller parameters so as to achieve a uniformly good response over the expected range of operating conditions. Although many adaptive control techniques have been proposed over the years, applications to process control have been limited. The major problems relate to reliability and robustness characteristics, the complexity of the algorithms for identification and parameter updating, and cost.

The purpose of this study is to examine the adaptive or self-tuning regulator problem in the context of a distributed, microprocessor-based control environment. The flexibility and modularity features of the new distributed control systems make it possible to implement special-purpose algorithms for the adaptive function in software rather than hardware, substantially reducing the cost factor. It also opens up much more favorable prospects for developing robust designs, fail-safe features, etc., which can tie in effectively with process monitoring and diagnostics functions. Finally, the distributed architecture is conducive to a multilayer hierarchical structure in which the direct control function (first layer) is implemented on a fast time scale and the adaptive function (including identification and parameter updating tasks) is carried out at a much slower time scale by a minicomputer (second-layer).

Some topics of interest in the proposed study are:

(a) Examine the trade-offs governing the distribution of tasks to be carried out by the microprocessors at the first layer, and those to be carried out by the

minicomputer at the second control layer.

(b) Study methods of aggregating the data at the first level so as to reduce the flow of information needed to be transmitted over the data link. Related problems are concerned with data link requirements during an update procedure, including questions of buffer store, interrupts, timing of the adaptive function, etc.

(c) The more general question of robustness of the system to various contingency events, e.g., a malfunction of a sensor or microprocessor, is also to be considered. It is essential to build in appropriate fail-safe and monitoring features to insure that the system will be able to "cope" over a wide range of such contingency occurrences.

6. *Process diagnostics*

Of increasing importance in the design of computer control systems for modern industrial processes is the need for timely and appropriate response to contingency events, e.g., a large change in a process variable, a fault in a control computer or a communication link, or failure of a sensor. As a result of the complexity and large-scale nature of these systems and the mixed continuous time/discrete-event nature of their behavior, existing design methodologies for achieving reliable and robust mechanisms for handling major disturbances and contingency events are inadequate. An essential component of the design of such mechanisms is the identification of the disturbances causing anomalous or dangerous behavior. Indications of failed components, a likelihood ranking of a set of possible failed components, a list of appropriate experiments to be performed to allow further deduction, a list of appropriate corrective actions, and the prediction of the effects of particular operator actions will provide considerable assistance to safe and reliable control of potentially dangerous processes.

An approach that we are investigating for diagnosing faults is based on elements of the theories of nonlinear filtering, linear filtering, and stochastic processes. Faults which are difficult to identify because of their low-level effect on the observed variables are grouped into two classes according to their impact on the process parameters: (1) those whose impact is sudden (modeled as jumps) and (2) those whose impact is gradual. This time-scale separation of two important classes of failures is one of the special features of the approach, and one which has strong motivation in industrial process applications (impending jump faults are often preceded by gradual performance degradation). Nonlinear filtering theory is then applied to the diagnosis of jump faults. The research entails an extensive analysis, simulation, and testing of the theory. The study will focus initially on a scalar dynamical system to provide insight for extending the approach to the more realistic multivariable case. A two-stage approach which makes a "coarse" diagnoisis of a class of failures followed by a "fine" determination of the specific failure is being investigated along with some other approaches. Finally, methods for diagnosing gradual degradations which are compatible with the final form of the method used for diagnosing jump faults are being formulated and tested. This involves the solution of a second multivariable nonlinear filtering problem.

Summary

Microprocessor-based distributed control systems represent a new approach to the control of complex industrial process systems. These control systems combine exciting possibilities for the realization of advanced control algorithms, hierarchical control and dynamic controller reconfiguration with attributes of flexibility, versatility, reliability, and maintainability.

This paper describes a major new research facility centered around a Foxboro SPECTRUM control system which will provide, together with instrumented test bed processes, an experimental base for the study of distributed hierarchical control applied to industrial process systems. The realization of many potential advantages of distributed control depends critically on the proper design of the structure, component interactions, control tasks, and the communication system. In this regard, we have outlined a sampling of research investigations presently being considered in such areas as microprocessor-based control algorithms, inferential control, hierarchical control and communication, and computer system structure and operation. The importance of the development of analytical tools for the design and analysis of these complex and highly interacting control systems will continue to grow as the application of such systems to the integrated control of industrial plants expands.

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He has been very active with IFAC since its inception. He has served as Chairman of its Technical Committee on Systems Engineering and is presently a Vice-chairman of its Technical Board. He has also served on various AACC committees and was an ADCOM member of the Systems, Man and Cybernetics Society.

Book Reviews

R. G. Jacquot, **Modern Digital Control Systems,** Marcel Dekker, Inc., 1981.

Reviewed by D. P. Petersen

"Never judge a book by its cover." This hoary adage finds fresh justification in *Modern Digital Control Systems*. The cover artwork depicts two blocks containing transfer functions in s, hardly a "modern" concept. There is no indication of the signal sampling or quantization essential for "digital" processing. No feedback path, the hallmark of "control." is evident, and the two blocks are not even interconnected to form a "system!"

Under the cover, the book improves dramatically and, in a thorough but surprisingly compact manner, takes the reader from an entrance level of conventional analog control theory through sampled-data theory, digital filters, conventional digital control, state-space analysis including the concepts of controllability and observability, quantization effects, stochastic signals, and optimal estimation and control. Five appendixes cover not only the algebraic details of z transforms and matrix manipulations as far as the Cayley-Hamilton theorem and a short introduction to system identification techniques, but also a set of suggested laboratory exercises in digital control and some useful BASIC language computer programs. The book appears to straddle senior/first year graduate level material. Its particular strong point is the inclusion of many numerical examples exhibiting continuity and progression of concepts, in that different control approaches are applied to a few representative plants. The exercises following each chapter enhance the book's utility for self-study as well as classroom use.

In the light of the book's achievements, its negative aspects appear as minor quibbles. Its production left it with many typographical and editorial errors, most of which are correctable by the reader but often with a residue of puzzlement, as between the identical equations (11.2.61) and (11.2.63) on page 278, and in the caption of Fig. 12.6 (p. 307) where "Rules" apparently suffered a transmutation from "poles." One wonders why, on page 130, the author uses the laborious and approximate series representation of e^{Ft} when his own Appendix E covers both diagonalization and the Cayley-Hamilton theorem. Or why, on page 274, a Gaussian density needs to be assumed when all the manipulations are limited to second-moment quantities. Or why, having introduced the "minimal prototype" controller on page 73 and state variable representations in Chapter 6, the simple "dead-beat" design, not requiring full state feedback, as on page 206, is omitted.

Appendix C includes a number of suggested laboratory exercises in digital control involving the interconnection of an analog computer (or simply a collection of operational amplifiers and passive components) simulating a continuous-time linear plant, and a digital controller. We are told that the latter incorporates A/D and D/A converters which require certain numerical constants (p. 326) in order to be callable from BASIC statements and that there exists a "package" of machine-language subroutines for such use, but presumably their development for any particular mini- or micro-computer is left as an exercise for the professor. Admittedly this is a highly system-dependent matter but once accomplished, standard control routines may be written in macro and avoid the clumsiness and slow execution of BASIC in realtime applications.

One might also bemoan the lack of reference, or even of lip-service, to nonlinear control applications, which in this reviewer's opinion are the true "promised land" of digital control with the prospect of enhanced performance coupled with simpler components and lower power consumption.

On the whole, this reviewer finds the book very suitable as a text for self-study or classroom use and a welcome addition to the growing library of literature on this topic.